SYNTHESIS AND CHARACTERIZATION OF PHASE INVERSION MEMBRANE WITH MOS_2

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Sihan Qiu

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SYNTHESIS AND CHARACTERIZATION OF PHASE INVERSION MEMBRANE WITH MOS_2

Approved by:

Dr. Crittenden John, Advisor
School of civil and environmental engineering
Georgia Institute of Technology

Dr. Yongsheng Chen
School of civil and environmental engineering
Georgia Institute of Technology

Dr. Xing Xie
School of civil and environmental engineering
Georgia Institute of Technology

Date Approved: 04/03/2019

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LIST OF SYMBOLS AND ABBREVIATIONS

PSF	Poly-sulfones
NMP	N-Methyl-2-pyrrolidone
MoS_2	Molybdenum disulfide
FO	Forward osmosis
RO	Reverse osmosis
PRO	Pressure-retarded osmosis
MPD	1,3-phenylendiamine
TMC	1,3,5-trimesoylchloride
CP	Concentration polarization
GO	Graphene oxide
XPS	X-ray photoelectron spectroscopy
ICP	Internal concentration polarization
ECP	External concentration polarization

SUMMARY

The aim of the project is to synthesize and characterize phase inversion membrane with MoS_2 and find the best way to reach its best performance.

MoS_2 is used as a nanocomposite to improvement membrane performance. MoS_2 can increase the water flux at an early stage when MoS_2 concentration is approaching 0.05% in FO and 0.1% in PRO under 1M or 2M sodium chlorine solution. Additional addition of MoS_2 can no longer increase the water flux because aggregated nanocomposites block part of pores in membrane. A membrane under higher osmotic pressure requires higher MoS_2 concentration to reach its best water flux.

The addition of MoS_2 into the membrane can affect reverse salt flux much greater than water flux. Even a small loading of MoS_2 can reduce reverse salt flux greatly compared to membrane without addition.

Membrane with MoS_2 has Mo part with a hydrophilic entrance and a tight center while S part with a hydrophobic entrance and an expanding center. An appropriate irregularity can help improve the performance of the membrane, but membrane with extra irregularity will lead to a decrease in water flux. The higher concentration of nanocomposite MoS_2 can lead to a

more hydrophilic active layer. With the concentration of MoS_2 continuously increases, relative intensity increases accordingly. However, after a certain concentration, the relative intensity remains the same or even decreases.

For membrane with 0.05%, 0.1% and 0.2% MoS_2, when the concentration of MoS_2 increases, relative intensity increases accordingly. However, as the amount of MoS_2 continuously increases to 0.5% and 1.5% the relative intensity doesn't change a lot.

CHAPTER 1. INTRODUCTION

There are three main concerns in the world nowadays, which are clean water, renewable energy and affordable healthcare.(T.S. Chung, 2012) Therefore, the technology to get clean water with lowest energy cost becomes especially important. Using membrane to treat water is a popular technology because of its efficiency and outstanding effect.(S. Lee 2010)

There are two kinds of membranes. One is symmetry membrane, the other is the asymmetry membrane. The membrane we make in this experiment is asymmetry membrane. It contains a support layer and an active layer with nanocomposite MoS_2.

Some challenges exists when we are trying to do water treatment. For example, we are lack of effective membrane to separate waste and clean water.(S. Lee 2010, O'Hern 2014, Surwade 2015) Also, we are lack of a good draw solution to extract water from the other side. A good membrane should have a high salt retention ability, high water flux, low concentration polarization and resistance to pH and stability.

1.1 Phase inversion membrane

In this experiment, we use phase inversion method to fabricate the support layer. Phase inversion method is one of the most popular method to fabricate polymeric membrane. It is a process by which a polymer is transformed from a liquid or soluble state to a solid state. The concept of phase inversion covers a range of different techniques such as immersion precipitation or 'diffusion-induced phase separation', thermal-induced phase separation, 'vapor-phase' precipitation and precipitation by controlled evaporation.(Mulder, 2000).

There are several advantages of phase inversion membrane, such as excellent toughness, high biocompatibility, high selectivity, simple making process, good film-forming performance, low cost and high porosity. The high porosity of the phase inversion is also one of the reasons that we choose it as the support layer in our case. These advantages maybe due to the unique process used to make the membrane, such as immersion precipitation. (T. Mohammadi 2009, D.Y. Xing 2010, Y.B. Cai 2017)

1.2 Nanocomposite MoS_2

Nanocomposite can be added to support layer to enhance membrane's performance. Nanoparticles as casting solution additives always affect the membrane structure, for example,

clay addition significantly affects the membrane internal and surface pore structures while it had no effect on porosity.(Zhu 2013, Yu 2014)

In this experiment, MoS_2 is used as a nanocomposite to improvement membrane performance. MoS_2 used in our case is a black powder shown as Figure 1 below.

Figure 1. Nanocomposite MoS_2

The addition of MoS_2 has many advantages.

First, membrane with MoS_2 is more stable. MoS_2 is stable both thermally and mechanically (W.F. Li, 2016). Its melting point is more than 1185 °C, which makes it thermally stable. Its mechanical strength enables it to treat water in harsh condition continuously. (Nørskov 2005, Li 2011)

Second, during chemical vapor process, vacancy can easily be introduced into MoS_2 monolayer. (W.F. Li, 2016).

Third, membrane with MoS_2 has higher water permeability compared to normal membrane. The high permeability characteristic is due to the structure of MoS_2. MoS_2 contains two elements, Mo and S. They form a fishbone structure, which enables it allows more water to permeate through. (M. Heiranian, 2015)(Zhou 2013) Some research also compare it to membrane with another nanocomposite graphene oxide (GO). The reason for why water permeability of MoS_2 is higher than GO is because MoS_2 is more hydrophilic. Membrane with MoS_2 has higher affinity to water due to more hydrogen bonding. Hydrogen bonding can create channel in membrane for water passage. (L.W. Sun, 2013)(Chou 2015) Besides, the water permeability has a linear relationship with applied pressure. The relatively higher pressure there is, the higher water permeability it has. (J. Azamat, 2017)

The size of pores in membrane can only let water molecules pass through, therefore, large ions will be rejected.(Chen 2001, Chou 2013, Yu 2014) That is why MoS_2 is also supposed to be good for the reverse salt flux.

Last but not least, MoS_2 is acid-alkaline-tolerant. From experiments, MoS_2 remains high rejection ratio at acidic solution at pH=2. (L.W. Sun, 2013)

1.3 Concentration polarization

From trials from others, we see some use membrane support layers from phase inversion and then add carbon nanotube to enhance its performance. (M. Amini, 2013; Y. Wang, 2013) Some use commercial membranes (J. Ren, 2014) like thin film composite membrane to characterize the performance of membrane. (J. R. M. N.N. Buli, 2012; M. L. L. N.N. Buli, E. M.V.Hoek, J. R.McCutcheon, 2011) Commercial membrane shows a stable performance in water treatment but relatively low water flux.

One of the difficulty most membranes are facing is concentration polarization. The issue was discovered by Mehta and Loeb (G.D. Mehta 1978, G.D. Mehta 1978) and Lee et al. (K.L. Lee 1981) after their PRO experiments revealed power outputs that were far below the outputs estimated based on theoretical osmotic pressure differentials. There are two kinds of concentration polarization which are internal CP(ICP) and external CP (ECP). Internal CP happens in the supportive layer while the external CP happens in the active layer. Internal concentration polarization (ICP) is mainly

responsible for water flux decline, especially higher draw solution apply in opposite direction of osmotic pressure gradient. Besides, a good membrane supportive layer is with low tortuosity, high porous and thin structure. (X. Song, 2011) So in this project we will try to use MoS_2 to improvement performance of membrane.

Concentration polarization refers to the emergence of concentration gradients at a membrane or solution interface resulted from selective transfer of some species through the membrane under the effect of transmembrane driving forces. (Wikipedia)

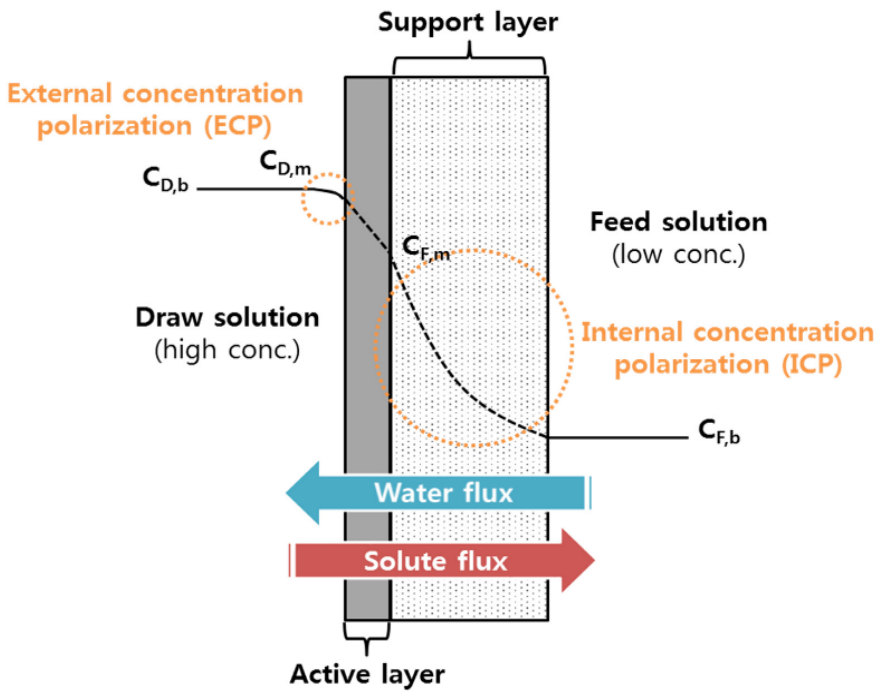


Figure 2. Concentration polarization

1.4 Applied pressure to the membrane

There are three kinds of membrane treatment technology classified by the applied pressure. (T. Y. Cath, 2006) There are forward osmosis, pressure-retarded osmosis and reverse osmosis. The following graph shows the three applied pressure.

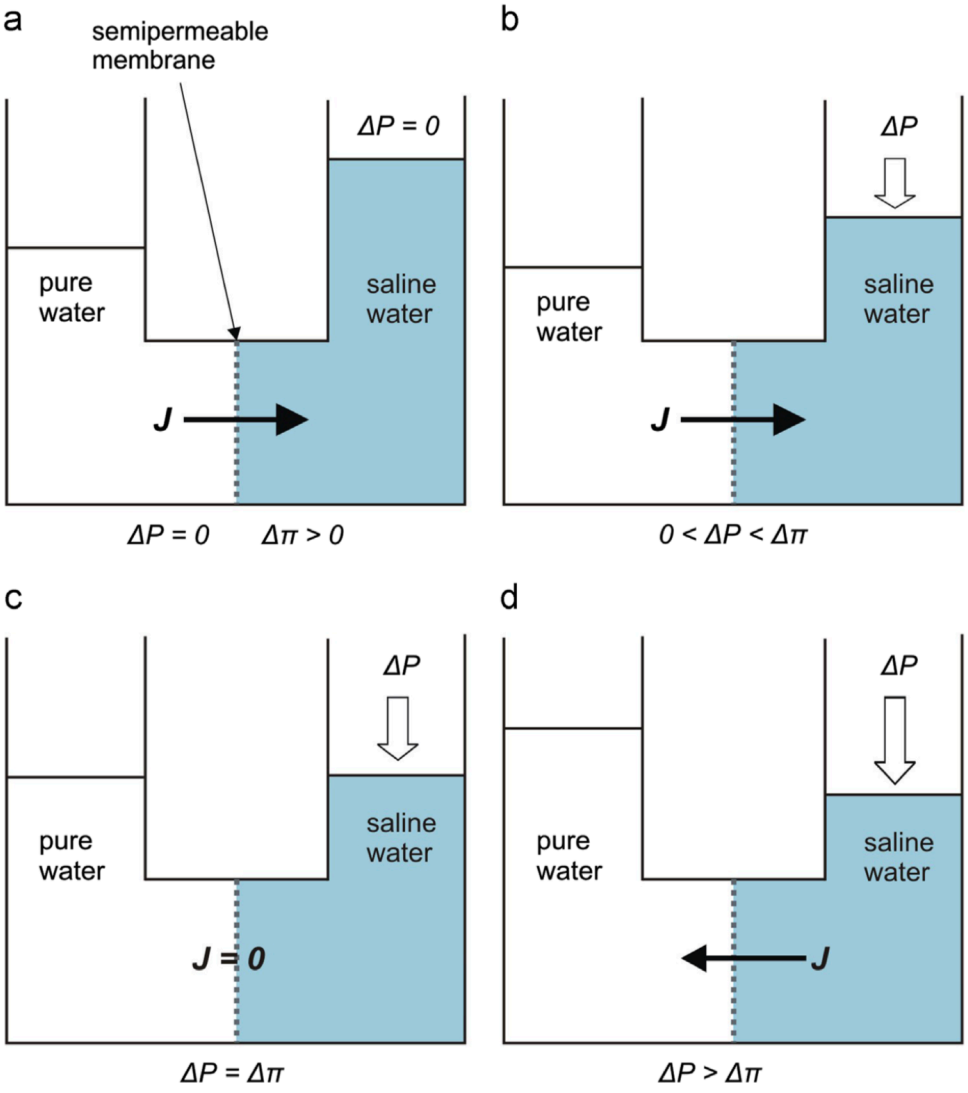


Figure 3. Forward osmosis, pressure-retarded osmosis and reverse osmosis

In Figure 3, Graph a shows the FO state with no applied pressure. Graph b shows the PRO state with applied pressure smaller than osmosis pressure. Graph c shows the state when applied pressure is equal to osmosis pressure. Graph d shows the situation when applied pressure is greater than osmosis pressure, which is called the RO state.

For forward osmosis , there is no applied pressure. For pressure-retarded osmosis, applied pressure is smaller than osmotic pressure. For reverse osmosis, applied pressure is larger than osmotic pressure difference. From the basic differences among these three methods, we can see the advantages of FO and PRO is its energy-saving property. The process of FO and PRO treatment is the diffusion of water through supportive layer and then diluting the draw water.

From all the literature, the value of forward osmosis membrane treatment is widely accepted because of its low operation pressure and temperature, potentially low fouling and less energy consumption. (T.S. Chung, 2012) And a lot of possible applications are listed, such as power generation, desalination, wastewater treatment and osmotic membrane bioreactor, etc. (S. Zhao, 2012) If energy can be saved in

these areas, our life can be easier due to the current large consumption. (Saren 2011)

PRO is also as economic and environmental friendly way to apply pressure. The membrane that is required for PRO don't need to as thick and tensile as membrane used in RO treatment because it don't have to stand for large pressure. (R.W. Holloway 2005) Besides, PRO method can also save energy. Although it required more energy then FO treatment method, it is still a energy saving way. As a renewable energy source with high environmental performance, it is expected that PRO will qualify for subsidy programs and other government incentives similar to those already seen today for wind and solar power. With subsidies included, the osmotic power cost could drop to \$0.05—\$0.06 kWh^{-1} in 2015. (S.E. Skilhagen 2006)

The problem now we are facing is how to make a perfect membrane to treatment in a cheap and high-efficiency way. An ideal membrane can gives high water flux, low reverse salt flux, a tensile strength and a wide pH range. (T.S. Chung, 2012)

The goal of my project is to find out why the addition of MoS_2 can maximize the water flux and minimize reverse salt flux of phase inversion membrane, how the addition of MoS_2 can change the surface and cross-sectional morphology of the

membrane and accordingly improve its hydrophilicity and what is the dosage of MoS_2 we can use under different applied pressure (FO and PRO) and different draw solution concentrations.

We need to find the best nanocomposite MoS_2 loading to synthesis a high water flux, low reverse salt flux and good hydrophilicity phase inversion membrane.

CHAPTER 2. METHODOLOGY

This chapter will be about the methodology to fabricate and characterize the membrane.

2.1 Nanocomposite MoS_2

The nanocomposite we use in this paper is not made from laboratory. We buy commercial MoS_2 from Sigma-Aldrich company Sold under Material Transfer Agreement with Mark Hersam group at Northwestern University. The commercial MoS_2 is shown to have more stable performance.(Bertolazzi 2011)

2.2 Support layer fabrication

To fabricate the support layer, we need to make the solution first. The polymer of the solution is PSF and the solvent of the solution is NMP. We use 4.5 g PSF to dissolve in 45.5 g of NMP and get 9 % (wt) of the solution. In our case, molybdenum disulfide is added into support layer. We change the concentration of MoS2 to find how its concentration affect the performance of membrane. The following table shows different concentration of MoS_2 in the support layer.

Table 1. Different concentration of MoS_2 in the support layer

	0	0.05% (wt)	0.1% (wt)	0.2% (wt)	0.5% (wt)	1.5% (wt)
Psf (g)	4.5	4.5	4.5	4.5	4.5	4.5
NMP (g)	45.5	45.5	45.5	45.5	45.5	45.5
MoS_2 (g)	0	0.025	0.05	0.1	0.25	0.75

The solution will be placed in the ultrasound machine for 20 min, stired for around 12 hours and stand for another 10 hours to make sure that PSF is completely dissolved and dispersed into NMP and there is no bubble in the solution.

After preparing the solution, solution is poured on a glass pane. A membrane scraper is used to scrape the solution uniformly on the glass. One point that worth mentioning during this process is that we need to make sure that there is no water on the membrane scraper or the glass pane. Any water drops on the tools will case holes on the support layer. Wiper and drier can be used to keep dryness. The thickness of the membrane is set to be 8 mm on the scraper.

Then, the glass pane is placed slowly and carefully into DI water to start phase inversion process. The phase inversion process usually takes about 4 to 5 hours to come to an end.

2.3 Active layer fabrication

The active layer is made of 1,3-phenylendiamine (MPD) solution and 1,3,5-trimesoylchloride (TMC) solution. For the MPD solution, we dissolve 1.5 g MPD in 100 ml water. For the TMC solution, we dissolve 0.15 g TMC in 100 ml hexane. Keep the solution in the ultrasonic wave oven for 2 min to keep it completely mixed.

After the solutions are prepared, we pour the MPD solution on the support layer. The solution is kept on the support layer for about 5 min. The 5 min time can guarantee MPD completely attach to support layer. The membrane is dried before the TMC solution is poured on the membrane. The TMC solution is kept on the membrane for about 1 min. To clean the remaining residual on the membrane, hexane is used to rinse the membrane. Finally, the membrane we made should be kept in the heat oven with 80°C for 8 min for desiccation.

2.4 Characterization of membrane

2.4.1 Characterization of water flux and reverse salt flux

After the fabrication of the membrane, we do characterization of the membrane. By using the test system, we test the water flux and the salt reverse flux of the membrane.

The test system contains a feed tank, a draw tank, two pumps, a computer and a test module. The feed tank and the draw tank contains clean water and draw solution. The computer is mainly responsible for recording the data. The main test process happens in the test model. Test system and test module are shown in the following Figure 4 and 5.

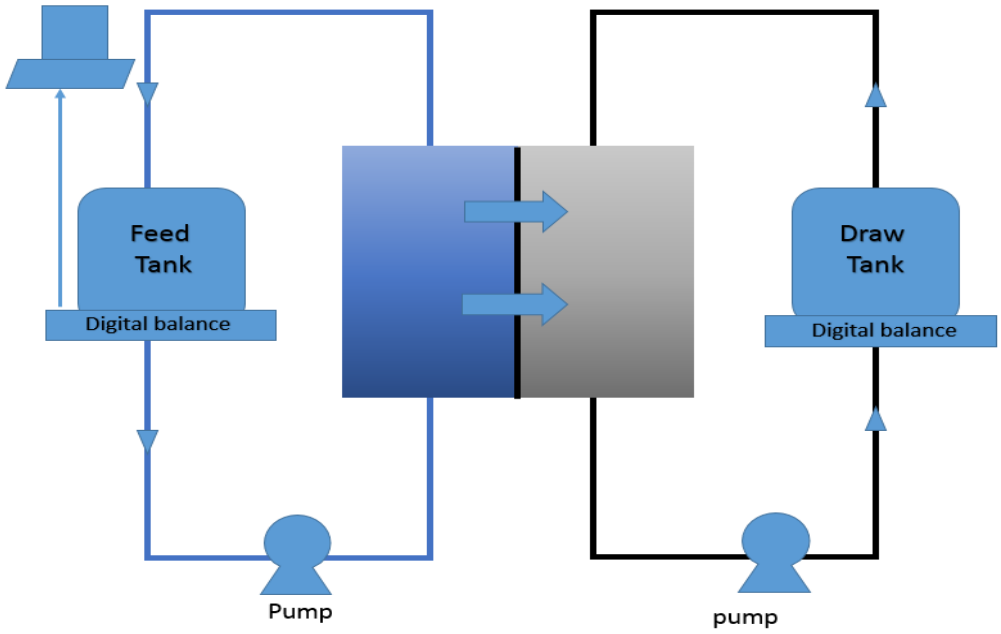


Figure 4. Test system

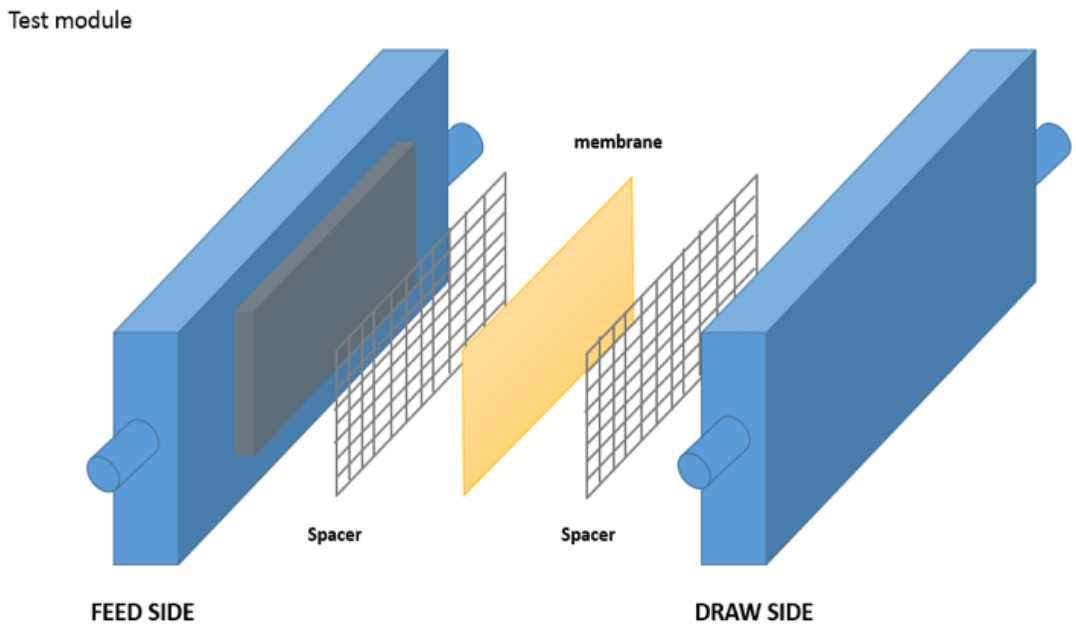


Figure 5. Test module

The feed side is linked to the beaker filled with DI water while the draw side is linked to the beaker filled with NaCl solution with specific concentration. The beaker filled with draw solution is linked to a weighing sensor. After we start two pumps, water moves in each side. Due to the osmotic pressure, water go from the feed side to the draw side. By collecting the data about weight change, we can calculate the water flux, the equation about the calculation is shown below,

$$J_W = \frac{\Delta m_{draw}}{\rho_{\mathrm{draw}} \mathrm{A}\, \Delta t} = \frac{\Delta V_{draw}}{\mathrm{A}\, \Delta t}$$

J_W: water flux,

Δm_{draw}: weight change of the draw solution,

ΔV_{draw}: volumn change of the draw solution,

ρ_{draw}: density of the draw solution,

A: area of the membrane,

Δt: the interval time of measurement.

During the process of the experiment, we also need to measure the conductivity of the feed solution at certain time interval (about 1 min). By comparing the graph of the conductivity-concentration standard curve, we can get the concentration of NaCl at certain time. The conductivity-concentration standard curve is shown as follows.

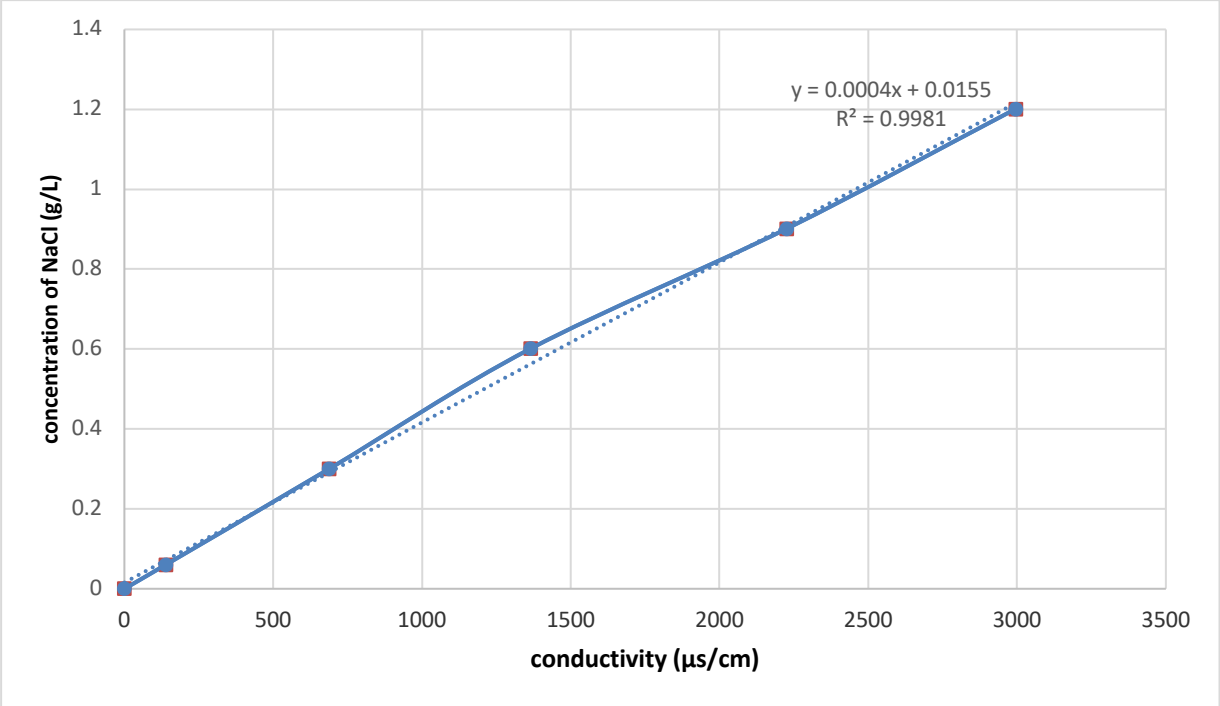


Figure 6. Conductivity-concentration standard curve

After we get the concentration of NaCl at the feed side at different time, use the equation below to calculate the salt reverse flux,

$$J_s = \frac{C_t V_t - C_0 V_0}{At}$$

J_s: salt reverse flux,

C_t: final concentration of salt,

V_t: final volumn of feed side

C_0: initial concentration of salt,

V_0: initial volumn of feed side

A: area of the membrane,

t: the interval time of measurement.

2.4.2 Characterization of surface morphology

To measure the surface morphology of the membrane, scanning electron microscope (SEM) method is used. Field emission scanning electron microscopy (FE-SEM) (Hitachi SU8230) was used to characterize the morphology of nanocomposite membranes.

Dried membrane samples were used. For the membrane cross-section characterization, the samples were prepared by

soaking membranes into liquid nitrogen and cutting them manually to get sharp cross sections. By watching the SEM images, we can get the surface morphology and structure of the membrane.

Porosity of the membrane can also be calculated. The equation is shown as follows.

$$\varepsilon = \frac{(W_1 - W_2)/\rho_w}{\frac{W_2}{\rho_m} + (W_1 - W_2)/\rho_w}$$

ε: membrane porosity,

W_1: weight of polymer in wet states (g),

W_2: weight of polymer in dry states (g),

ρ_w: density of water (g/ml),

ρ_m: density of polymer (g/ml).

2.4.3 Characterization of contact angle and hydrophilicity

By testing contact angle, we can know the hydrophilicity of the membrane. The contact angle is defined as the angle, conventionally measured through the liquid, where a liquid–vapor interface meets a solid surface. It quantifies the wettability of a solid surface by a liquid via the Young

equation. The smaller the contact angle, the more hydrophilic the membrane is. Based on the different contact angles, we can define the state of membrane by the following five types, which are spreading state, good wetting state, incomplete wetting state and no wetting state.

Ramé-hart Model 250 goniometer (Ramé-hart Instrument Co.) was used to measure the water contact angle. By changing the concentration of the nanocomposite, we can also know about the relationship between the nanocomposite and hydrophilicity of the membrane. A best loading of MoS_2 can be concluded from that to get the best membrane hydrophilicity. We can also compare the hydrophilicity result with our result of water flux, see if membrane with higher hydrophilicity can have relatively higher water flux and thus, better performance.

2.4.4 Characterization of elements in the membrane

To know elements composition in the membrane XPS technique are used. XPS can get the elemental composition through quantitative spectroscopic technique. It is a surface-sensitive quantitative spectroscopic technique that measures the elemental composition at the parts per thousand range, empirical formula, chemical state and electronic state of the elements that exist within a material. (Wikipedia)

By using the XPS technique, we can find out what types of elements exists on the membrane. The result image from the X-ray photoelectron spectroscopy will contain peaks indicating what kinds of elements we have in the membrane.

Apart from that, by testing different membrane samples with different MoS_2 loading, we can also see how MoS2 concentration affects the peak of element Mo. Also, whether membrane with higher MoS_2 concentration will have higher relative intensity of element Mo. If not, with the addition of nanocomposite MoS2, if there is other phenomenon happens in the membrane.

CHAPTER 3. MEMBRANE CHARACTERIZATION AND ANALYSIS

This chapter will be about the characterization of membrane including water flux, reverse salt flux, surface morphology, contact angle and hydrophilicity and element analysis of the membrane.

3.1 Water flux and reverse salt flux

Parallel method is used in this experiment, so for each condition, three trials are used to get an average data to reduce error.

We get water flux and reverse salt flux data for both FO and PRO conditions. Two concentrations of draw solutions are used, which are 1M and 2M NaCl solution. Six types of membrane with different MoS_2 concentration are used as introduced in Table 2. The following table and graph shows the result.

Table 2. Water flux and reverse salt flux for FO under 1M and 2M NaCl

MoS2 loading %		Flux (LMH)		Reverse salt flux (GMH)	
		1M	2M	1M	2M
0	FO	3.2	4.65	6.25	12.924
0.05		5.47	10.44	0.31	0.65
0.1		3.56	6.41	0.35	4.58
0.2		1.94	2.98	0.16	6.73
0.5		1.94	2.07	0.194	0.08
1.5		1.38	1.76	0.83	0.6

Table 3. Water flux and reverse salt flux for PRO under 1M and 2M NaCl

MoS2 loading %		Flux (LMH)		Reverse salt flux (GMH)	
		1M	2M	1M	2M
0	PRO	6.17	8.29	14.15	21.35
0.05		4.68	3.51	1.08	0.11
0.1		11.77	12.6	5.02	5.89
0.2		5.71	4.41	8.94	8.43
0.5		4.01	4.58	0.55	2.56
1.5		3.1	3.52	0.61	1.09

Based on the table above, the corresponding figures are shown as below.

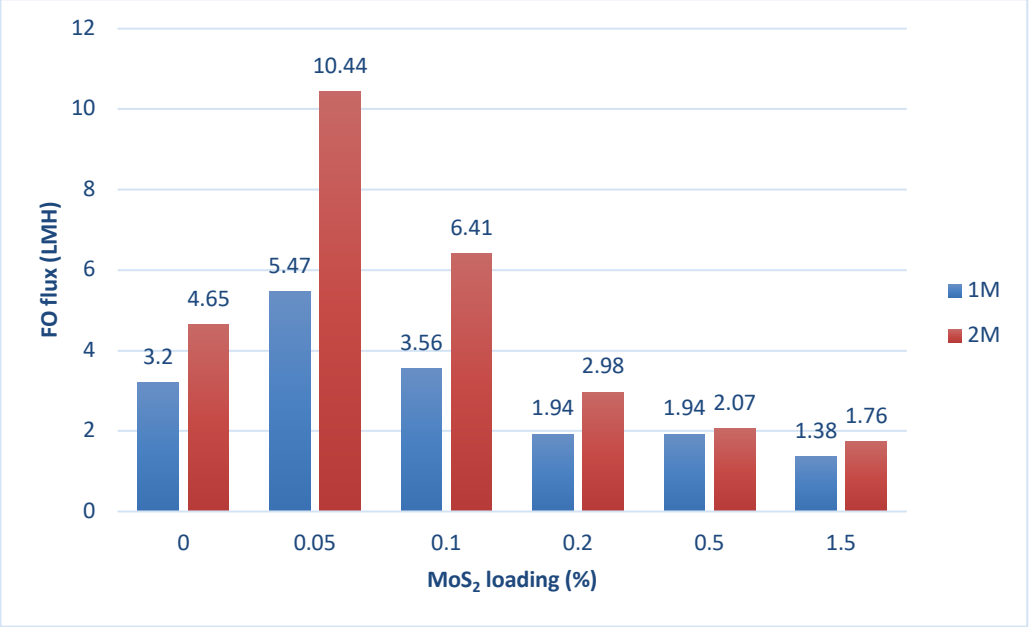


Figure 7. Water flux FO under 1M and 2M NaCl

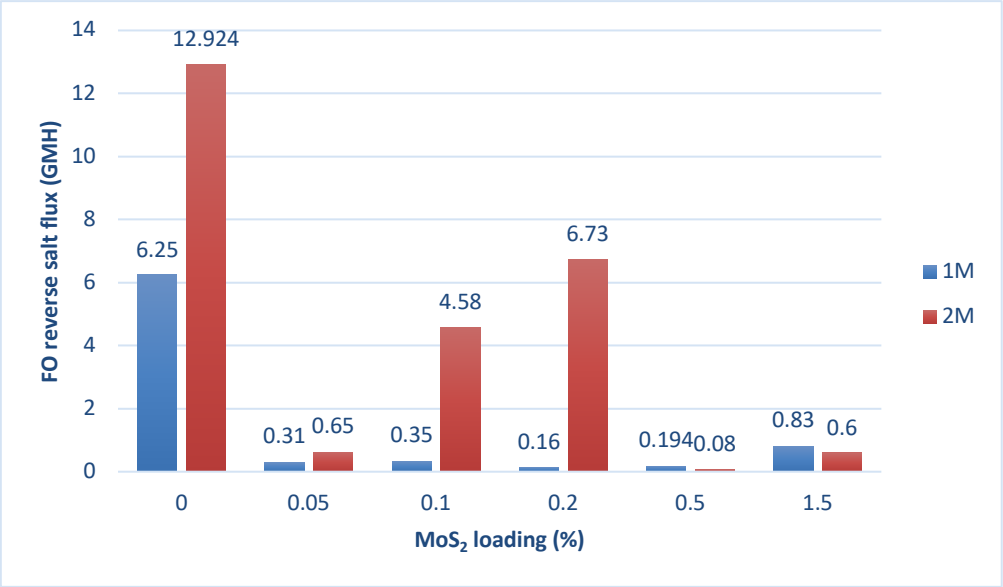


Figure 8. Reverse salt flux FO under 1M and 2M NaCl

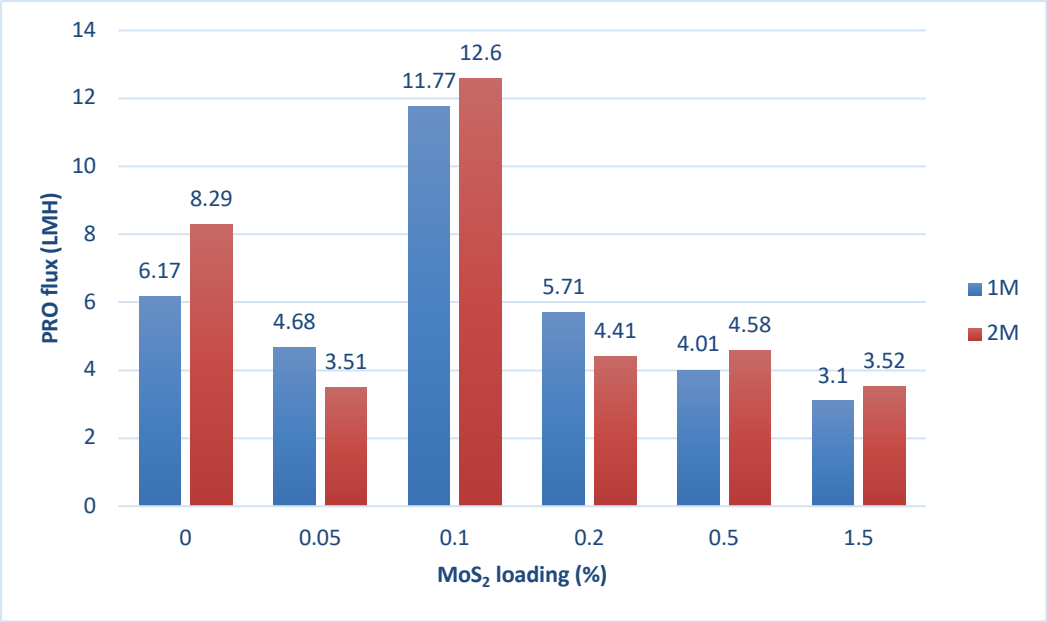


Figure 9. Water flux PRO under 1M and 2M NaCl

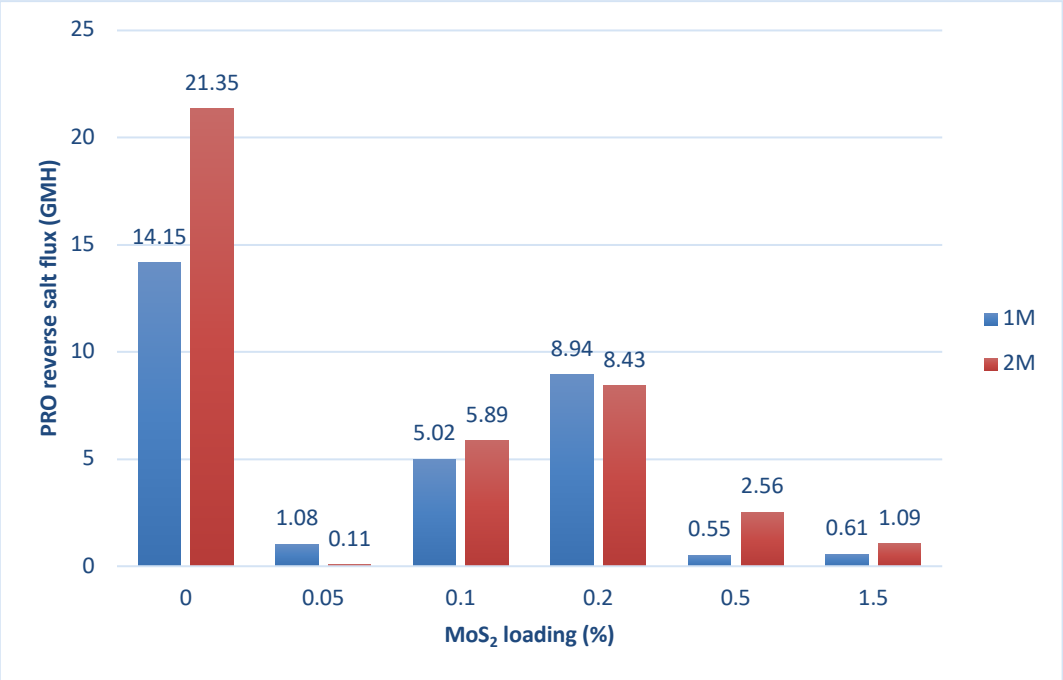


Figure 10. Reverse salt flux for PRO under 1M and 2M NaCl

From Figure 5 and Figure 6, we can see that for FO, when MoS_2 concentration is around 0.05%, a maximum water flux and a minimum reverse salt flux is shown. The addition of MoS_2 can greatly increase water flux and decrease reverse salt flux at an early stage. However, with the continuous addition of MoS_2, water flux decreases and reverse salt flux increases accordingly. This shows that there exists an appropriate point where is most suitable for water flux and reverse salt flux. A possible reason for that point is due to aggregated nanocomposites MoS_2 block parts of pores in membrane when the concentration of MoS_2 is high during synthesizing. The blocked pores can no longer let water flux to pass through.

Similarly, from Figure 7 and Figure 8, the best MoS_2 concentration for PRO is around 0.1% when it has the largest water flux and a relatively small reverse salt flux. Therefore, 0.1% MoS_2 loading is best point for PRO case.

In sum, appropriate loading of MoS_2 is crucial in membrane's water flux and reverse salt flux performance. Appropriate amount of MoS_2 can help increase water permeability and reject ions.

In addition, a membrane under higher osmotic pressure requires higher MoS_2 concentration to get its best performance. Besides, we can see that the addition of MoS_2 into the membrane can reduce reverse salt flux greatly. Even if the membrane has low concentration of MoS_2, its reverse salt flux is still obviously smaller than membrane without MoS_2.

3.2 Surface morphology

To find the surface morphology of the membrane, SEM technology is used to help us have a visual cognition of the membrane. The following graph is the image from SEM.

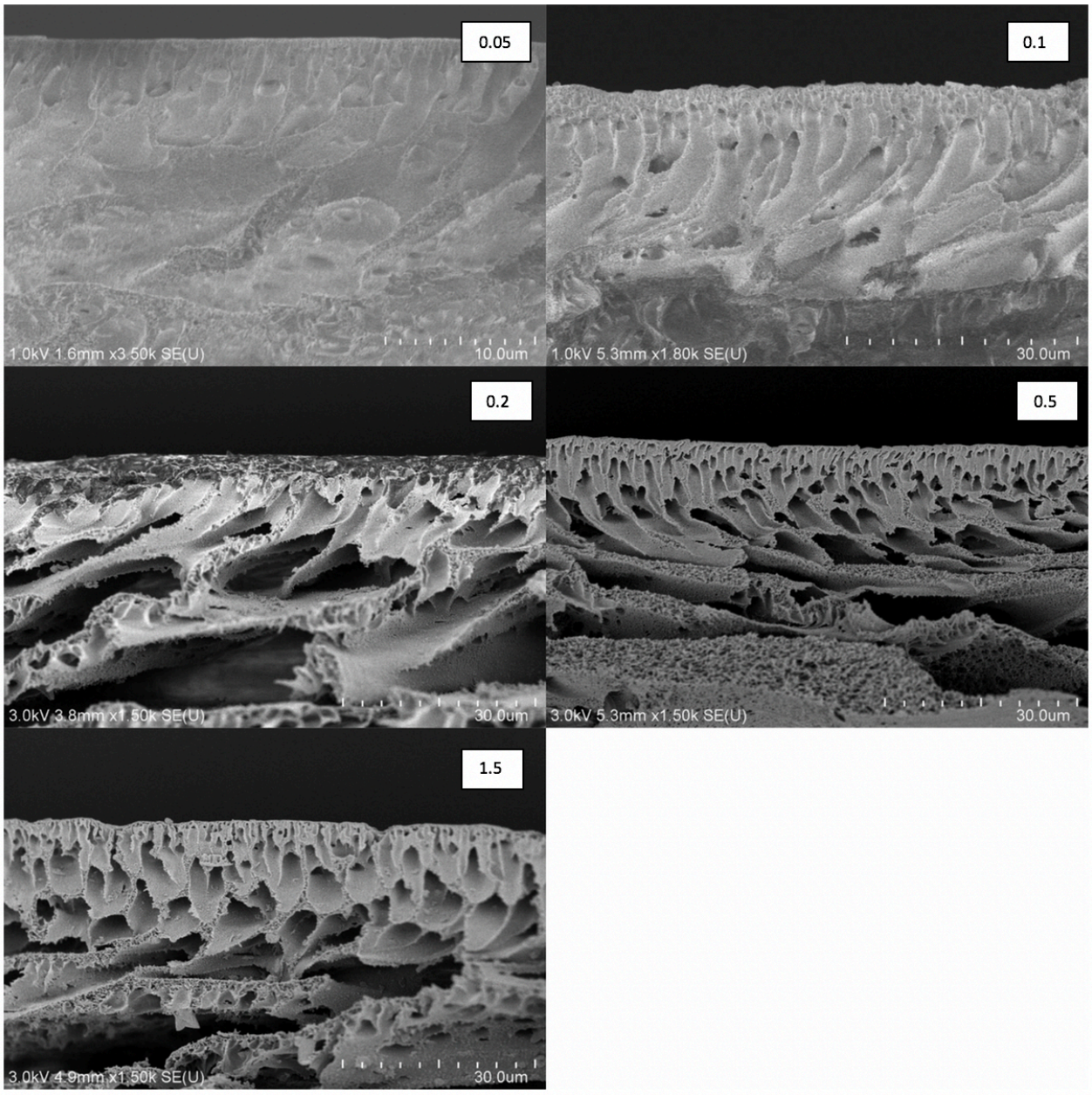


Figure 11. SEM results for membrane intersection when concentration of MoS_2 is 0.05%, 0.1%, 0.2%, 0.5%, 1.5%

From the cross-sectional SEM graph shown in Figure 6., we can find the structure of the MoS_2 membrane, unlike the structure of GO with flat entrance and flat exit, has Mo part

with a hydrophilic entrance and a tight center while S part with a hydrophobic entrance and an expanding center. This results in the membrane pore structure to be rugged.

Furthermore, as we can see from the trend of the above five image, the higher the MoS_2 concentration, the more rugged the pore structure will be.

An appropriate irregularity can help improve the performance of the membrane, but membrane with extra irregularity will lead to a decrease in water flux. The result corresponds to the result in section 3.1, where the water flux first increases with the loading of MoS_2 together, however, when the loading of MoS_2 exceeds a certain amount, water flux drops accordingly.

3.3 Contact angle and hydrophilicity

The following graph shows the contact angle of the membrane when the concentration of MoS_2 varies.

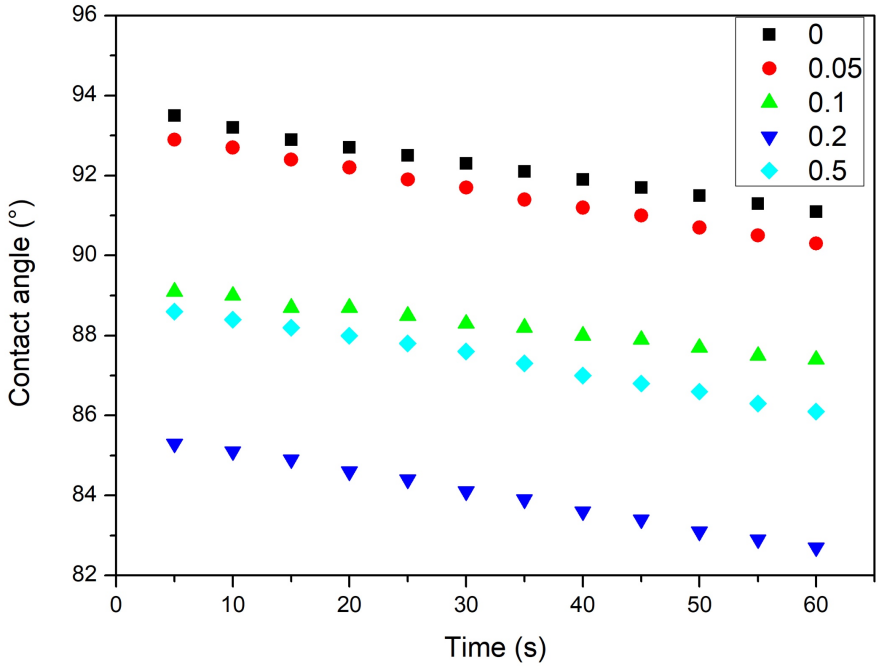


Figure 12. Contact angle results for membrane intersection when concentration of MoS_2 is 0, 0.05%, 0.1%, 0.2%, 0.5%, 1.5%

From Figure 12, we can see that the higher the initial MoS_2 concentration, the smaller the initial contact angle is.

This shows that the presence of MoS_2 can increase the hydrophilicity of the active layer. As time moves on, active layers with higher concentration of MoS_2 decrease its contact angle faster than ones with smaller concentration of MoS_2. The results show that the presence of higher concentration of MoS_2 can increase the hydrophilicity of the active layer faster than layers with lower concentration of MoS_2.

In addition, the relationship between the contact angle and the water flux is also compared. As we can see from Figure 6, the trend of water flux under increasing MoS_2 concentration is ascending accordingly. The result shows that the higher the concentration of MoS_2 is, the larger the water flux will be.

From the discussion above, we can conclude that the higher concentration of nanocomposite MoS_2 can lead to a more hydrophilic active layer, which can also result in a higher water flux.

3.4 Element analysis

XPS technology is used to analyze elements in the membrane. All the peaks on the image of XPS shows an element correspondingly.

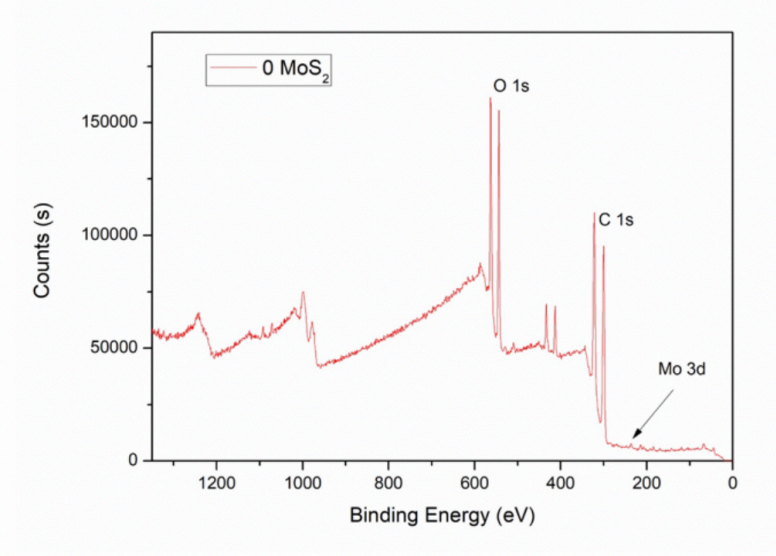
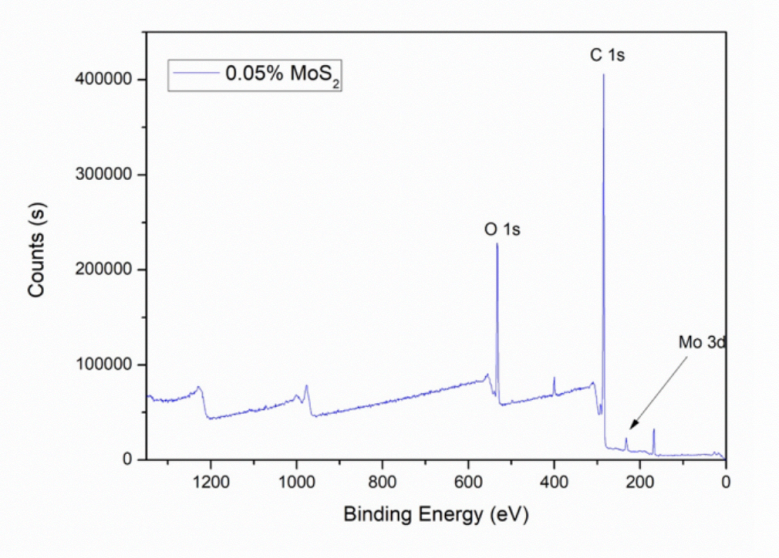
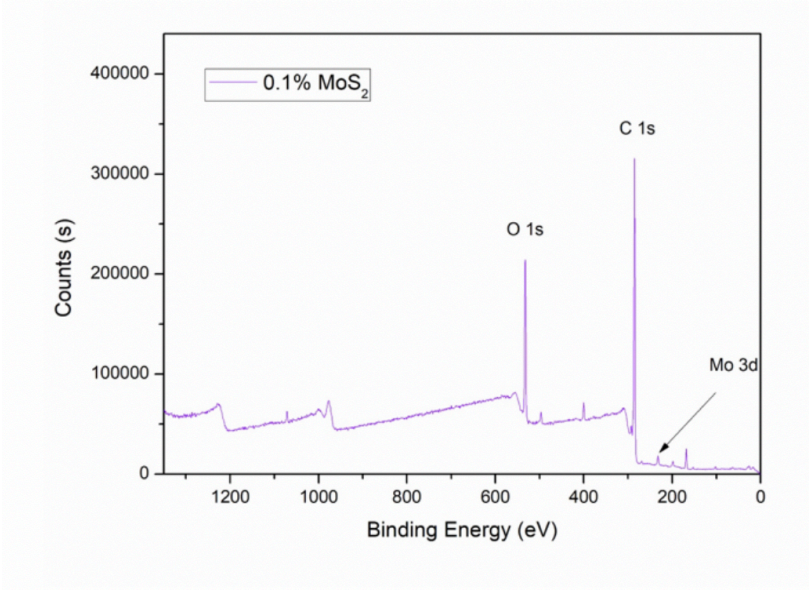
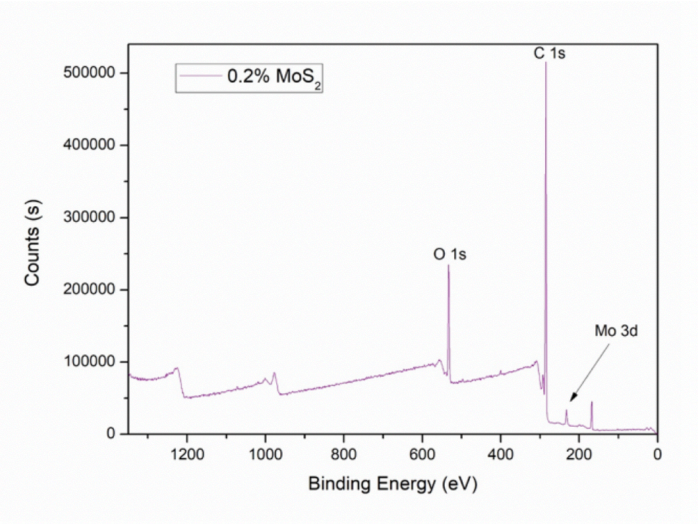


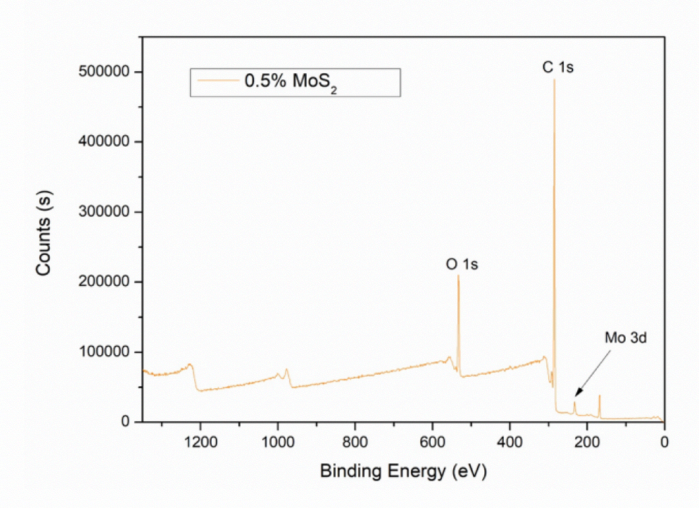
Figure 13. XPS results for membrane intersection when concentration of MoS_2 is 0

From Figure 13, membrane without MoS_2 is not showing a peak representing element Mo.






0.2% MoS2
C 1s
O 1s
Mo 3d
Counts (s)
Binding Energy (eV)
500000
400000
300000
200000
100000
0
1200
1000
800
600
400
200
0


0.5% MoS2
C 1s
O 1s
Mo 3d
Counts (s)
Binding Energy (eV)
500000
400000
300000
200000
100000
0
1200
1000
800
600
400
200
0

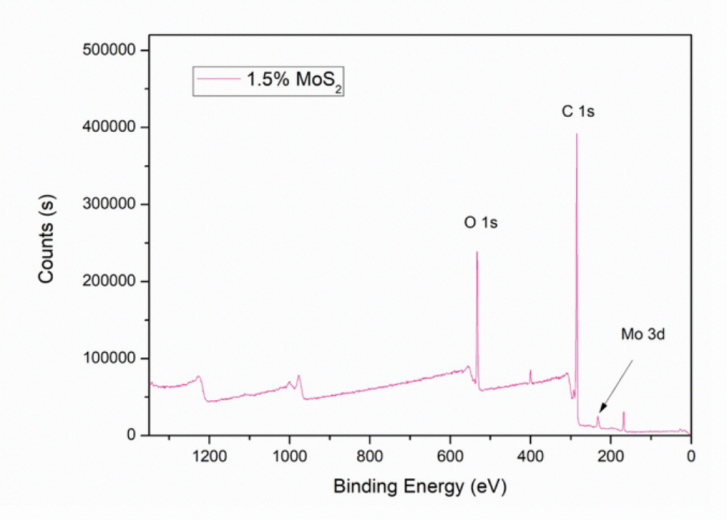

1.5% MoS2
C 1s
O 1s
Mo 3d
Counts (s)
Binding Energy (eV)
500000
400000
300000
200000
100000
0
1200
1000
800
600
400
200
0

Figure 14. XPS results for membrane intersection when concentration of MoS_2 is 0.05%, 0.1%, 0.2%, 0.5%, 1.5%

From Figure 14 XPS results, we can see that all membranes having addition of MoS_2 has an obvious peak at element Mo. This shows that element MoS_2 is successfully added into the membrane.

Then, we are going to compare the Mo curve for the above six images. Since the peak for Mo is not clearly shown on the overall curve, we take curve for Mo as a separate image and put them together in one image.

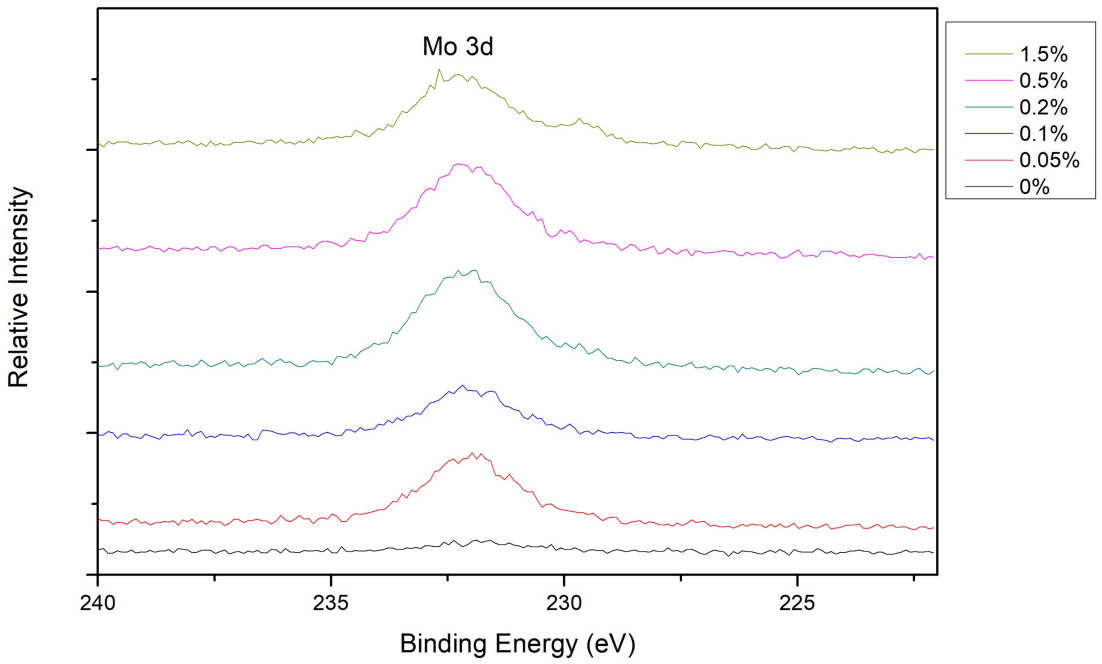


Figure 15. XPS results with augmented Mo curve

From Figure 15, we can see that membrane without Mo has no peak. For other membranes with MoS_2, the slope of the peaks can show the amount of MoS_2 at the surface. For membrane with 0.05%, 0.1% and 0.2% MoS_2, with the concentration of MoS_2 increases, relative intensity increases accordingly. However, as the amount of MoS_2 continuously increases to 0.5% and 1.5% the relative intensity doesn't change a lot.

The reason for this may be because nanocomposites aggregate at the inner space of the membrane which leads to less nanocomposite on the surface. Besides, error of the experiment can also lead to some accidental data.

CHAPTER 4. CONCLUSIONS

From the result of experiment, we can see that the addition of nanocomposite MoS_2 can actually improve the performance of the phase inversion membrane.

In terms of water flux and reverse salt flux, MoS_2 can increase the water flux at an early stage when the concentration of MoS_2 is around 0.05% in FO and 0.1% in PRO because the structure of MoS_2 can enable water to permeate better. However, if more MoS_2 is added into the support layer than needed, aggregated nanocomposites will block the pores and thus reduce the water flux. A membrane under higher osmotic pressure requires higher MoS_2 concentration to reach its best performance. The addition of MoS_2 into the membrane has more influences to reverse salt flux than water flux. Even a small loading of MoS_2 can reduce reverse salt flux greatly compared to membrane with no addition.

In term of the structure of MoS_2, membrane with MoS_2 has Mo part with a hydrophilic entrance and a tight center while S part with a hydrophobic entrance and an expanding center. An appropriate irregularity can help improve the performance of the membrane, but membrane with extra irregularity will lead to a decrease in water flux.

In terms of hydrophilicity of the membrane, a higher concentration of nanocomposite MoS_2 can lead to a more hydrophilic active layer with small contact angle, which leads to a higher water flux.

From the XPS image, we know that MoS_2 is successfully added into the membrane. With the concentration of MoS_2 increases, relative intensity increases accordingly. However, after a certain concentration, the relative intensity remains the same or even decreases. This is because nanocomposites aggregate at the inner space of the membrane which leads to less nanocomposite on the surface.

In sum, the addition of the MoS_2 into the membrane support layer can increase its water flux, decrease its reverse salt flux and increase its hydrophilicity to improve the overall performance of the membrane.

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